

Implementation of a Low-Cost, Commercial Orbit Determination System

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Abstract

This paper describes the implementation and potential applications of a workstation-based orbit determination system developed by Storm Integration, Inc. called the Precision Orbit Determination System (PODS)[™]. PODS is offered as a layered product to the commercially-available Satellite Tool Kit (STK)[®] produced by Analytical Graphics, Inc. PODS also incorporates the Workstation/Precision Orbit Determination (WS/POD)[™] product offered by Van Martin Systems, Inc. The STK graphical user interface is used to access and invoke the PODS capabilities and to display the results. WS/POD is used to compute a best-fit orbit solution to user-supplied tracking data.

PODS provides the capability to simultaneously estimate the orbits of up to 99 satellites based on a wide variety of observation types including angles, range, range rate, and Global Positioning System (GPS) data. PODS can also estimate ground facility locations, Earth geopotential model coefficients, solar pressure and atmospheric drag parameters, and observation data biases. All determined data is automatically incorporated into the STK data base, which allows storage, manipulation and export of the data to other applications.

PODS is offered in three levels: Standard, Basic GPS and Extended GPS. Standard allows processing of non-GPS observation types for any number of vehicles and facilities. Basic GPS adds processing of GPS pseudo-ranging data to the Standard capabilities. Extended GPS adds the ability to process GPS carrier phase data.

1. Introduction

1.1. Problem Background

The Precision Orbit Determination System (PODS)[™] grew out of a need to process antenna tracking data to determine a spacecraft orbit. The determined orbit can then be used to generate antenna pointing commands to control a ground antenna. Such a system is necessary for full "closed-loop" satellite command and control (i.e., from processing of telemetry and tracking data to the transmission of commands) and augments commercial command and control systems such as Storm's Intelligent Mission Toolkit (IMT)[™].

1.2. Requirements

A workstation-based capability is desired for compatibility with other workstation-based products, including the IMT. The system should function stand-alone, but offer interfaces for integration with other products. A Commercial Off-the-Shelf (COTS) product approach is desirable for potential resale either alone or integrated with other command and control products. Finally, the development and certification costs must be kept low, which suggests incorporation of existing, proven COTS products in the design as much as possible.

1.3. Solution Approach

Storm has chosen two commercial products for incorporation into PODS: Satellite Tool Kit (STK)® by Analytical Graphics, Inc. (AGI) of King of Prussia, PA, and Workstation/Precision Orbit Determination (WS/POD)™ by Van Martin Systems, Inc. (VMSI) of Rockville, MD. PODS consists of these products as well as the additional code and data required to integrate the products, accept user inputs and provide output data in operationally useful formats.

In order to support customers with different requirements, PODS is available in three options:

1. Standard - Provides basic capability for parameter estimation using the ground-based measurement types (angles, range and range-rate). Does not process any Global Positioning System (GPS) data types besides position vectors.
2. Basic GPS - Includes the capabilities of Standard PODS and adds the ability to process GPS pseudo-range and navigation data.
3. Extended GPS - Includes all of the capabilities of Standard and Basic GPS PODS, and adds the ability for processing of GPS carrier phase data.

The remainder of this paper discusses the two commercial products (STK and WS/POD), how they are used within PODS, an operational description of PODS, and suggestions for application of PODS to different missions.

2. COTS Product Descriptions

2.1. Satellite Tool Kit

STK is a workstation-based, interactive system for analyzing the relationships among satellites, Earth-bound vehicles, ground stations and targets. STK incorporates both text-based tables and graphics to display satellite orbits, periods of visibility, access times, and sensor coverage patterns for multiple satellites, ground stations and targets. The graphics allow animation of satellite constellations to see how sensor coverage and visibilities change over time and with orbital position.

STK allows the input of initial orbit conditions for satellites, facility and target coordinates, and Earth- and satellite-based sensor parameters via ASCII text file or Motif-based user interface panels. Output is displayed via graphical ground traces on a variety of map projections, and tables of access angles and ranges over windows of visibility. Both text and graphics output can be sent to files for printing and/or incorporation into other systems.

STK allows the specification of different orbit propagation methods, including two-body, J2 and J4 perturbations, processing of NORAD 2-Line Mean Element Sets (2LMES), and the optional High-Precision Orbit Propagator (HPOP) from Microcosm, Inc., which performs numerical integration of the satellite equations of motion based on a high-fidelity environmental force model. All propagation methods require input of initial conditions at a specified epoch time. The 2LMES (which can be loaded automatically through an external interface) contain an epoch time, initial orbit conditions, and other modeling parameters.

The STK user interface uses an object-oriented approach for defining and manipulating data. For example, a Scenario object consists of multiple Vehicle, Facility and/or Target objects. Each of these in turn may have one or more Sensor objects. Objects are created, saved, and restored

separately. Data for objects are stored in individual ASCII files with pre-defined extensions (e.g., ".v" for vehicle files, etc.).

Through the addition of optional add-on modules, STK provides a highly accurate and sophisticated operational mission planning capability. For example, Pacific Sierra Research, Inc. (PSR) offers an scheduling capability known as the Generic Resource Event and Activity Scheduler (GREAS), which combines STK-generated orbit and visibility information with user-entered events to construct mission time lines. AGI's Visualization Option (VO) offers high-resolution three-dimensional graphic visualizations of vehicle attitudes, orbits, and relationships to ground targets and other vehicles. Other products like these can be added in a modular fashion to construct a mission planning environment to meet specific requirements.

2.2. STK Programmer's Library

The Satellite Tool Kit/Programmer's Library (STK/PL)[™] offers C application programmers access to the underlying functionality of the STK runtime version. The STK/PL includes header files and selected source code modules to allow programmers to develop add-on applications that are seamlessly integrated with the STK user interface, or stand-alone applications that use STK/PL as a library of functions. The STK/PL includes access to the object manager, user interface, and graphics, as well as astrodynamics libraries, time and coordinate conversion functions, and the orbit propagators. The STK/PL is written in an object-oriented manner which allows rapid modification and addition of new functionality. The PODS User Interface is being developed using the STK/PL.

2.3. Workstation/Precision Orbit Determination

WS/POD is a state-of-the-art precision orbit and geodetic parameter determination software system derived from the GEODYN II Version 8609 software used by NASA's Goddard Space Flight Center (GSFC). Van Martin Systems, Inc. has ported the GEODYN II software to numerous workstation platforms, enhanced it in the area of GPS data processing, and packaged it as a commercially available and supported product.

WS/POD processes satellite tracking data using a Bayesian weighted least-squares data reduction algorithm and detailed environmental modeling using a Cowell-type numerical integration scheme to determine precisely various quantities related to the satellite orbit and tracking stations. Specific capabilities include the following:

Physical Models

- Atmospheric drag using the Jacchia 1971 atmospheric density model
- Solar radiation pressure
- Earth gravitation (up to 180 x 180 geopotential matrix)
- Polar motion
- Earth rotation
- Solid Earth tides
- Third body gravitation
- Earth precession and nutation
- Tropospheric refraction

Measurement Types

- Laser and radar range
- Radar range rates and dopplers (including single and double differences)
- Radar altimeter range
- Topocentric right ascension and declination
- East and north direction cosines
- X/Y angles relative to the tracking station
- Azimuth/elevation angles relative to the tracking station
- GPS pseudo-range and carrier phase, including single, double and triple differences

Parameters Estimated

- Orbit state vectors
- Parameters of atmospheric drag and solar radiation pressure
- Measurement and time tag biases
- Tropospheric refraction scale parameters
- Satellite and station clock polynomials
- Earth gravitational coefficients
- Tracking station coordinates

Algorithms and Capabilities

- Cowell-type numerical integration
- Bayesian weighted least-squares estimation algorithm
- Batch data processing
- Automatic data editing with criteria specified by the user
- Simultaneous estimation of up to 99 satellite orbits in a single run

WS/POD is implemented as a series of stand-alone programs as detailed below. When a WS/POD run is performed, the required programs are executed in sequence, with the outputs from one forming the inputs for the next.

1. FixClock - Corrects GPS data for transmitter (GPS vehicle) and receiver clock errors. Estimates carrier phase ambiguities and resolves carrier phase cycle slips (GPS options only).
2. GPS Data Formatter (GDF) - Performs selection and correction of GPS receiver data and navigation information. This program is used only for applications requiring processing of GPS tracking data.
3. Tracking Data Formatter (TDF) - Performs data selection and editing for non-GPS tracking data.
4. WS/POD Control (CNTL) - Performs the input/output intensive portions of the WS/POD processing and accepts most of the user-control information.
5. WS/POD Executive (EXEC) - Performs most of the numerical work, including integration of the equations of motion and the statistical data fitting process.

Figure 1 shows the processing and data flow for a complete WS/POD run. The programs receive input and produce output exclusively through files. There is no user interface provided. Program control is provided by input files of 80-column card images with data in rigidly-defined column format. Data is provided and produced in ASCII text and binary files, with the file formats defined in the WS/POD documentation.

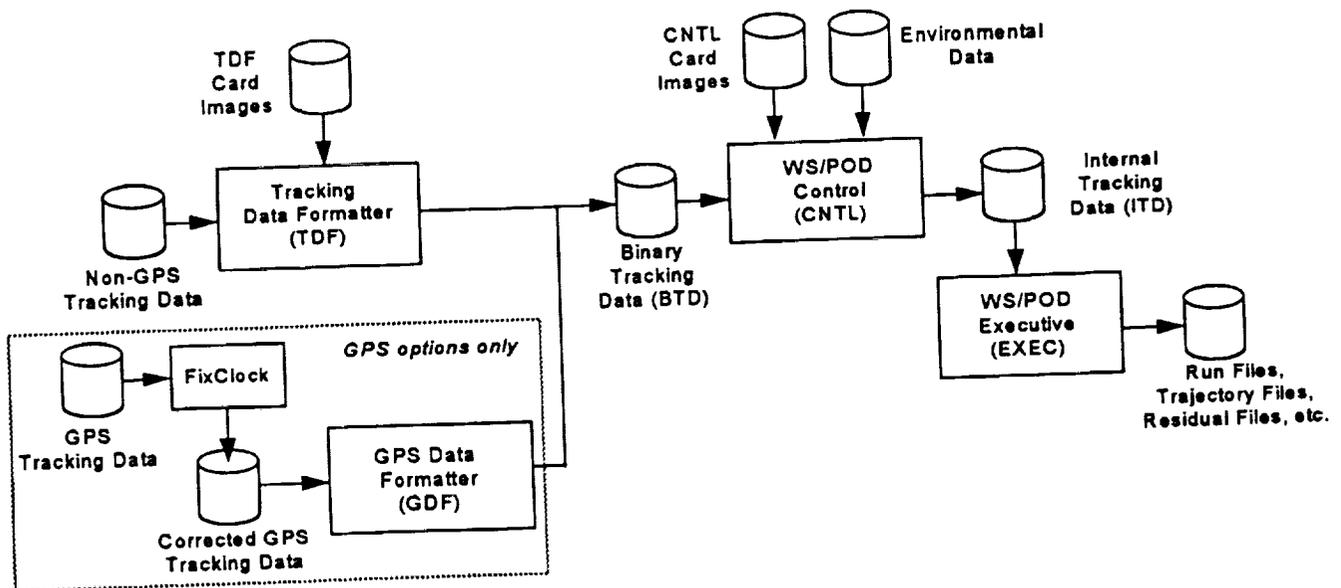


Figure 1: WS/POD Execution and Data Flow

2.4. Summary of Products

Both STK and WS/POD are true COTS products, each with an established customer base, full documentation, vendor support for questions/problems, and available maintenance and upgrades. STK offers a state-of-the-art graphical user interface that has been perfected through many years of development, upgrades and customer feedback. WS/POD offers more algorithmic and data processing capabilities that any other commercially-available orbit estimation system. WS/POD also benefits from its NASA heritage, which assures that the algorithms have been tested using a wide range of operational scenarios over a span of decades. The combination of the two products in PODS results in an orbit estimation system with unmatched ease-of-use and computational power.

3. Solution Approach and Features

The PODS design separates the PODS functionality into two components: PODS User Interface and the PODS External Procedure (PODS/XP). PODS User Interface is implemented using STK/PL. PODS/XP is a stand-alone program independent from STK that provides a C-language interface to WS/POD. The PODS functional breakdown is shown in Figure 2 and further described below.

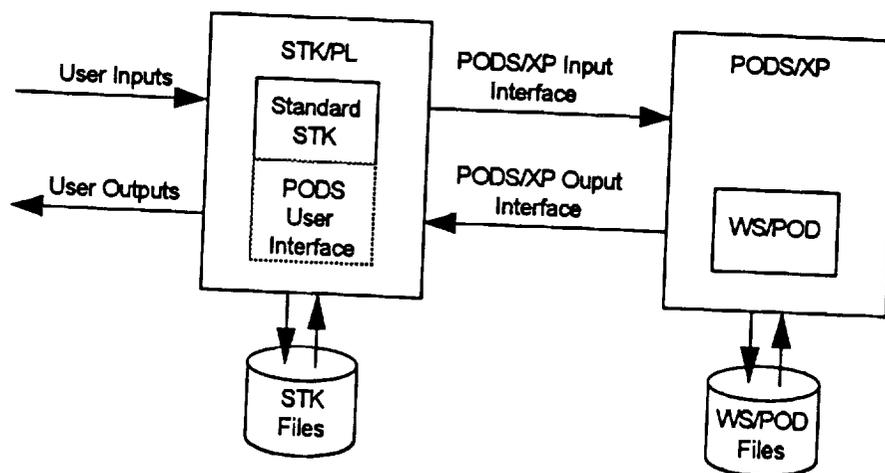


Figure 2: PODS Functional Breakdown

3.1. PODS User Interface

PODS operations are implemented as extensions to the existing STK operations and are invoked via the pull-down menus on the STK Browser Window. Input data panels appear in the STK Utility Window. The PODS input panels are similar to the existing STK panels, providing a Motif look-and-feel, pull-down menus, context-sensitive help, and standardized range and data format checking. A sample PODS input panel is presented in Figure 3.

Figure 3: Sample PODS Input Panel

The PODS interface offers the capability to access panels in sequence or directly. Accessing the next or previous panel in a sequence is accomplished using the NEXT and PREVIOUS buttons respectively. The DISMISS button removes the current input panel from the display with no values saved. The OK button updates all the values in the current panel sequence. For data requiring an indeterminate number of entries, a MORE button is provided which accepts the inputs on the current panel and re-displays a blank panel to allow more entries.

STK provides an object-oriented user interface in which the data entered on the panels in the Utility Window applies to the object (either Vehicle, Facility or Scenario) selected in the Browser Window. PODS data is treated as an extension to the data for the existing STK object class. PODS input panels are accessed using a "PODS Data" operation added to the STK *Utilities* menu for each object. This allows STK to store the PODS user inputs in the STK object files and use previously-entered values as defaults for subsequent runs. This approach also allows PODS input data to be specified in the ASCII object files instead of through the user interface.

Numerical outputs from PODS are displayed in the standard STK output data window which allows scrolling through the output data, exporting to files, queuing to a system printer, and real-time units and time format conversions. Selected PODS data (e.g., ephemeris and facility locations) are entered into the existing STK data structures, allowing STK to display the data graphically and use it as the basis for accesses and other computations.

In addition to the input panels for each object type, PODS offers two entry points for the STK user: Orbit Determination and Orbit Propagation. The interface to each is described further below.

Orbit Determination

The PODS Orbit Determination capability is invoked as an option from the Scenario-level STK *Utilities* menu. The Orbit Determination options presented are:

- **Modify Estimation Parameters** - This option gives the user access to a series of input panels which allow specification of the data applying to the entire run, including editing controls, force modeling controls and environmental parameters.
- **Select Tracking Data** - This option brings up an input panel allowing the user to select the tracking data files and the specific tracking data types and data spans to use for this run.
- **Select Output Files** - This option allows the user to select and specify names for optional output files and to select options pertaining to the contents of the selected output files.
- **Perform Estimation** - This option invokes WS/POD to perform the statistical data fitting process. Estimated parameters are displayed numerically in the STK output data window and graphically in the STK map window.
- **Perform Database Maintenance** - This option allows the user to specify the files containing environment data including solar/lunar/planetary ephemeris, Earth gravitational field model coefficients, Earth polar motion parameters, and solar and magnetic flux values. This option also provides a utility for updating the polar motion, UT1 and flux data tables.
- **Select Optional Outputs** - This option presents a menu which allows the user to select a variety of optional outputs to display after the estimation run.
- **Specify GPS Data** - This option allows the user to specify the data selection and editing parameters for the processing of GPS data. This option is only offered as part of the GPS options of PODS.

Orbit Propagation

The orbit propagation capability of PODS is implemented in STK as an additional propagator type and is accessed from the STK *Utilities/Orbiting* menu in the same manner as the other propagator types (Keplerian, J2, J4, etc.). The orbit propagator is used to extend the ephemeris span of previously-determined orbits. Note that the initial orbit state must be generated via a previous PODS run; i.e., it cannot be entered directly on the PODS orbit propagation panel. The current orbit state and epoch is shown on this panel as a display-only field for reference.

3.2. PODS External Procedure

The PODS External Procedure (PODS/XP) provides a C-language interface to the WS/POD product. It is designed to be independent from the specifics of the user interface, which allows the use of other user interfaces or calls from external applications.

PODS/XP provides four major operations:

- **Provide Tracking Data Summary** - This operation accepts the tracking data file names as input and produces a summary of the data for display to the user. The TDF and other utilities of WS/POD are used to read the tracking data files and extract the summary data.
- **Update Tables** - This operation accepts updates to the flux, polar motion and UT1 data in ASCII format and produces a new binary data file used by WS/POD. Off-line WS/POD utilities are used to read the data and produce the updated binary file.
- **Perform Orbit Determination** - This operation accepts tracking data, a priori parameter estimates, editing controls and selection criterion and uses WS/POD to compute a best-fit solution along with ephemeris and other optional outputs.
- **Propagate Orbit** - This operation uses WS/POD to extend the ephemeris span of an existing vehicle orbit.

The interface data are consolidated in a series of structures in header files that are incorporated by the application providing the data (initially STK/PL). PODS/XP is designed such that calls to it can be made from any C program that makes use of the PODS structures.

4. PODS Product Description

4.1. Processing Levels

PODS is offered in three levels to support users with a variety of mission requirements. All levels provide the STK-based graphical user interface and input/output capabilities. The different levels are licensed externally, allowing users to upgrade without re-installation of the PODS software. Each level is described in more detail below.

4.1.1. Standard

The Standard level provides the capability to determine all of the parameters and process all of the measurement types listed in 2.3. Workstation/Precision Orbit Determination with the exception of GPS pseudo-range and carrier phase data. Position vectors obtained using GPS receivers (or by any other means) can be processed by this level.

Sub-meter orbit accuracies are achievable depending on spacecraft altitude, tracking data accuracy/coverage, and physical models invoked.

4.1.2. Basic GPS

The Basic GPS level provides all of the capabilities of the Standard level and adds the ability to process GPS pseudo-range data from any number of GPS satellites and receivers. The receiver data is entered in the form of standard ASCII Receiver Independent Exchange (RINEX) files. Accompanying navigation data files also in standard ASCII RINEX format allow automatic correction of the GPS receiver clocks. The RINEX file formats are documented in GPS bulletins published by the National Oceanic and Atmospheric Administration (NOAA).

To achieve a more accurate solution using GPS data, PODS estimates the orbits of the GPS satellites based on the tracking data rather than using the satellite positions in the navigation files. The Basic GPS option contains parameterizations by Aerospace Corporation of detailed solar radiation pressure models developed by the satellite manufacturer (Rockwell International) to improve the accuracy of the determined GPS orbits.

4.1.3. Extended GPS

The Extended GPS level offers all features of the Standard and Basic GPS levels plus the ability to process carrier phase data. The Extended GPS level provides sophisticated algorithms to combine carrier phase data with other measurement types to resolve range ambiguities and remove cycle slips. Input GPS receiver data is provided in the RINEX file format as with the Basic GPS option.

With the addition of carrier phase data, orbit position accuracies within 10 cm and ground station coordinate accuracies within 1 cm are possible.

4.2. Inputs

The type, format and purpose of all PODS inputs are documented in the PODS User Manual. This section summarizes the available inputs.

4.2.1. Inputs from User

PODS user inputs are provided per STK object (Scenario, Vehicle, or Facility). Scenario inputs apply to all vehicles and facilities in the Scenario. Inputs per object type are listed below.

Scenario Inputs

- Input tracking data file names and formats
- Selection criteria for tracking data by time span, measurement type, vehicle or facility, etc.
- Earth flattening coefficient
- Earth gravitational constant and sigma value (if being estimated)
- Maximum geopotential model degree and order for all vehicles
- Earth gravitational model coefficients and sigma values (if being estimated)
- Solar flux data and times
- Magnetic flux data and times
- Coordinate system reference date
- Data pass definitions
- Minimum and maximum number for both arc and global iterations
- Arc and global convergence criteria
- Arc and global sigma editing criterion
- Arc and global initial RMS values
- Orbit integrator step size
- Selection of optional output reports as listed in 4.3.1. Outputs to User

Facility Inputs

- Minimum elevation angle before data is rejected
- Facility coordinates (in a variety of coordinate systems) and sigma values (if being estimated)
- Coordinate system for station adjustments
- Facilities which are constrained in position relative to one another
- Earth semi-major axis and flattening overrides for geodetic conversion per station
- Antenna mounting type and displacement

Vehicle Inputs

- Transponder delay
- Geopotential model degree and order to be used in the force model for this vehicle
- Vehicle area and mass
- Initial orbit state vector in a variety of coordinate systems and element forms (Cartesian, Keplerian, non-elliptical forms, etc.)
- Span for orbit estimation and/or propagation
- Optional unmodeled acceleration and sigma values (if being estimated)
- Solar pressure coefficient and sigma value (if being estimated)
- Atmospheric drag coefficient and sigma value (if being estimated)
- Biases and sigma values (if being estimated) for all measurement types, including
 - Simple (additive) biases
 - Scale (multiplicative) biases
 - Simple (additive) time bias
 - Satellite clock drift up to third order (GPS options only)
- Covariance matrix for initial orbit elements
- Selection of optional output files

Additional GPS Inputs (GPS options only)

- Names of RINEX files containing GPS tracking data
- Names of navigation files containing GPS navigation data
- Time span and/or measurement type criteria for selection/deletion of GPS data
- Radiation pressure model name for GPS orbit perturbations
- Identification of hub receivers used in construction of single differences

Facility Inputs (cont.)

- Nominal received wavelength
- Turn-around factor (ratio of wavelength transmitted to wavelength received)
- Biases and sigma values (if being estimated) for all measurement types (see list for vehicles above)
 - Simple (additive) biases
 - Scale (multiplicative) biases
 - Tropospheric refraction scale bias
 - Simple (additive) time bias
- Override sigma values for normal equations and data editing
- Temperature, pressure and humidity at facility and time spans over which the data applies

Additional GPS Inputs (GPS options only), cont.

- Allowed tolerances between receiver times when forming differences
- Selection of optional output data

4.2.2. Inputs from Files

4.2.2.1. Observation Data Files

PODS supports processing of observation data supplied in the following file formats:

- PCE Data Format
- GEODYN Binary Format
- GEOS-C Card Image Format
- Binary Metric Tracking Format
- RINEX Format (GPS options only)

The PCE and GEOS-C formats are ASCII. The others are binary. All formats are described in detail in the PODS documentation.

4.2.2.2. Environmental Files

Geopotential Model File

The Geopotential Model File is an ASCII file containing values for the coefficients of the Earth geopotential matrix. A default version is supplied with PODS and new versions may be created by the user using estimated coefficient values from PODS runs.

Flux, Polar Motion and UT1 Tables File

This is a binary file containing information relating to solar and magnetic flux, polar motion, and time conversions. The file contains the following information:

- A1-UTC data
- A1-UT1 data
- Polar motion data
- Solar flux data
- Magnetic flux data

This file must be periodically updated by the user as new information becomes available. PODS provides a table update utility for updating the binary file when new information is obtained. The format of the data is described in the PODS documentation.

JPL Planetary Ephemeris Data File

This is a binary file of solar/lunar and planetary ephemeris in the range January 18, 1957 to December 31, 1999. It is supplied with the PODS delivery and cannot be changed by the user. New versions of the file are supplied to the user by the PODS vendor as necessary.

4.2.2.3. STK Object Files

The user input data is stored as extensions to the STK object class definitions. Each STK object class has an associated ASCII file format in which the STK and PODS inputs are stored. The file formats are described in the STK and PODS documentation.

4.3. Outputs

4.3.1. Outputs to User

All user outputs are displayed through the STK user interface. STK provides the ability to change display units and time systems, export data into a format suitable for use by a spreadsheet program, and send data directly to a system printer. The Mandatory Outputs are displayed during or after every PODS run, and the Optional Outputs can be displayed in addition to the Mandatory Outputs at the user's choice. The items in each output type are listed below.

Mandatory Outputs

- Tracking data summary, including:
 - Vehicles, facilities and observations types for which tracking data exists in the selected files
 - Start and stop time of selected tracking data by vehicle, facility and observation type
 - Number of passes
 - Time span for each pass
 - Vehicle, facility and observation types per pass
- Convergence status (converged/diverged) for global and arc solutions
- Convergence criterion for global and arc solutions
- Number of global and arc iterations performed

Optional Outputs

- Correlation and covariance matrices for solved-for parameters
- Last iteration residuals
- Number of observations per type used in each iteration
- Summary per observation type, including:
 - Name
 - Units
 - Total number of measurements in tracking data
 - Number used
 - RMS and mean value of both the residual and weighted residual
- RMS history per iteration
- GPS vehicle orbit elements (GPS options only)

Mandatory Outputs (cont.)

- List of parameters estimated
- For each estimated parameter:
 - A priori value
 - Estimated value before last iteration
 - Final estimated value
 - Difference between final and a priori values
 - Difference between final and last iteration values
 - Final sigma value
 - Final sigma value multiplied by the RMS value
 - Epoch times (for estimated orbits)
- List of STK objects updated
- Ephemeris data (including ground traces) for each estimated orbit
- New locations for each estimated facility

Optional Outputs (cont.)

- WS/POD TDF Run File
- WS/POD TDF Block Summary File
- WS/POD GDF Run File (for GPS options only)
- WS/POD FixClock Run File (for GPS options only)
- WS/POD CNTL Run File
- WS/POD EXEC Run File (132-column)
- WS/POD EXEC Terminal Output File (80-column)

4.3.2. Outputs to Files

4.3.2.1. Solution Files

PODS allows the user to specify any of the following WS/POD files to save after the PODS run along with path names for the files. Note that the estimated orbits and other parameters, vehicle orbit ephemeris and facility locations are automatically stored in the STK object files.

TDF Files

- Binary Tracking Data (BTD) Format File
- ASCII TDF Run File
- ASCII Block Summary File

EXEC Files

- Binary Trajectory File
- Binary Residual File
- Binary Partial Derivative File
- Binary V-Matrix Format File (Force Model Partial Derivatives)
- Binary S-Matrix Format File (Solution Matrix) *or* Binary E-Matrix Format File (Normal Equations)
- ASCII Inertial Cartesian Ephemeris
- ASCII Keplerian Ephemeris
- ASCII Earth-Fixed Cartesian Ephemeris
- ASCII EXEC Terminal Output File (80-column)
- ASCII EXEC Run File (132-column)

CNTL Files

- ASCII CNTL Run File

FixClock Files (GPS options only)

- ASCII FixClock Run File

GDF Files (GPS options only)

- ASCII GDF Run File

The formats and contents of these files are outlined in the PODS documentation.

4.3.2.2. Environmental Files

PODS provides the ability to update the Geopotential Model File with the latest estimates of the Earth geopotential model coefficients. In addition, the PODS Flux, Polar Motion and UT1 Tables File update capability outputs a new ASCII master file and a new binary Flux, Polar Motion and UT1 Tables File. See 4.2.2.2. Environmental Files for a further description of these files.

4.3.2.3. STK Object Files

The STK object files containing PODS data are updated when the corresponding STK objects are saved in the same manner as the baseline STK. Saved input data appears as panel defaults for the associated object in the next PODS run.

5. Applications

5.1. Single Satellite Maintenance

One potential application for PODS is the Air Force Satellite Control Network (AFSCN), which determines the orbit of individual satellites using azimuth, elevation and S-band range and range-rate from a world-wide network of Remote Tracking Stations (RTSs). Tracking data is generated by the stations and sent to a Mission Control Complex where an orbit estimation is performed. The new orbit is used to generate antenna pointing angles, which are in turn sent to the RTSs to drive the antenna for subsequent contacts with the vehicle.

A typical sequence of events using PODS is as follows:

- The analyst creates the vehicle in the STK database including the initial orbit estimate. This can either be the result of a previous PODS run propagated to the present time, or generated by STK using NORAD 2LMES inputs.
- The tracking data from the RTSs are reformatted into a PODS data format. This can be accomplished using a database management system, custom program, or text formatting tool such as UNIX awk.
- The analyst produces a tracking data summary as necessary to display the types and spans of tracking data available.
- After approval of the tracking data contents, the analyst sets the estimation parameters and performs a PODS estimation run, resulting in a display of solution data and a ground trace for the new vehicle orbit.
- After examination of the output, the analyst can elect to accept the results by saving the vehicle object in STK, or can delete the results by reloading the original vehicle object from the data base.
- The analyst invokes the standard STK *Access* operation against the saved orbit ephemeris data to generate antenna pointing angles for the RTSs.
- After viewing the pointing angles, the analyst can export the data to a file for use in controlling an antenna in real-time.

The saved PODS results supply the input field defaults for the next PODS run for the same vehicle. The PODS-generated ephemeris data is used by other STK utilities including VO and GREAS. The analyst can also at any time extend the ephemeris span of a PODS orbit by invoking the PODS orbit propagator from the STK *Vehicle/Orbiting* menu.

5.2. Automated Constellation Management

One of the powerful features of the PODS implementation is the ability to process the data for many satellites simultaneously. This allows management of entire constellations from a single workstation. The nature of the STK interface and object file storage capability allows inputs to be specified by an automatic process, eliminating the need for a user to manually enter data for each run.

As an example of such a process, consider a constellation of several dozen low-flying satellites at high inclination (as is proposed for several commercial global cellular communications networks). Tracking data for the satellites is collected by multiple ground stations around the world. A process utilizing PODS is as follows:

- Collect the tracking data for the different stations.
- Using a network management system (such as Storm Integration's IMT) perform the following:
 - Reformat into PODS tracking data types. Data from multiple stations and/or vehicles can be included in a single PODS tracking data file.
 - Automatically generate the PODS inputs and build the STK ASCII object files containing the PODS inputs per object.
 - Invoke PODS for the entire constellation. Graphical results for the entire constellation appear in STK and can be displayed in high-resolution 3-D graphics using STK/VO.
 - Automatically save the estimated results for the entire constellation.
 - Use the Inter-process Communication (IPC) features of STK to automatically generate scheduling information, ground station access times and antenna pointing angles for the constellation.
- The analyst can perform periodic updates of the solar and magnetic flux information, Earth polar motion and UT1 coefficients using the PODS database management utilities, or these can also be automated.
- Manual overrides can be used at any time, entered either through the user interface or the object files.

Initial orbit estimations may require multiple passes of data in order to accurately estimate the effects of solar pressure, atmospheric drag, and the Earth gravitational field per vehicle. Longer data spans using multiple stations can also be used to precisely determine the location of the tracking stations as well as any biases associated with the measurements from the individual tracking stations. The best estimates of these parameters can be used in the automated scenario described above and can be updated at any time.

5.3. GPS Data Processing

PODS provides a variety of options for GPS data processing. The simplest option is supported by the Standard level and involves incorporation of GPS receiver point position vectors into an orbit solution. Vehicles with on-board GPS receivers generally telemeter the position vectors computed by the receiver. These position vectors can be combined with ground-based measurement types (e.g., range, range-rate, etc.) to form a single set of data for which PODS will compute the orbit that best fits the available data. The GPS receiver data can supplement ground-based measurement types, which can reduce the number and/or required coverage areas of ground stations while still achieving high accuracy. The GPS data can also be used as a reference to calibrate the ground-based receivers.

A more sophisticated approach can be supported when the on-board GPS receiver passes along the raw pseudo-range and carrier phase data. The GPS options of PODS can process these data types directly to obtain user satellite position solutions with 10 cm accuracy. Processing of pseudo-range and carrier phase data from ground-based receivers allows determination of ground receiver locations as well as orbit solutions for the entire GPS constellation with uncertainties below 1 m.

6. Summary

PODS combines two powerful COTS products, STK and WS/POD, into a single integrated system combining ease-of-use with high-fidelity algorithms. STK provides a modern graphical user interface and seamless integration of the estimated parameters with a wide range of existing mission planning and analysis tools. Current STK users will find PODS to be a natural extension of the existing STK capabilities, while new users will find the user interface easy to learn. WS/POD provides powerful computational capabilities with demonstrated reliability due to the heritage from NASA programs.

The COTS nature of PODS provides an end user with toll-free help lines, commercial-quality documentation, and available maintenance and upgrades. Costs of bug fixes and upgrades are spread out over the entire install base rather than being absorbing by a single customer. The system is designed so that it can be entirely configured by the end user with minimal assistance from the vendor.

Applications of PODS range from single satellite control to constellation management. The three different processing levels based on inclusion of different types of GPS data allow the user to choose the level of support appropriate for mission requirements. The open nature of the PODS/STK interfaces allow easy integration with existing command and control systems.

7. References

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